Precision Neutrino Oscillation Measurements using Simultaneous High-Power, Low-Energy Project-X Beams

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The recent measurements of non-zero $\sin^2(2\theta_{13})$[1, 2, 3, 4] ~~mean that it may be possible to detect CP violation~~ in the neutrino sector, and ultimately, to make a precision measurement of the CP phase, δ_{CP}; ~~this is one of the~~ primary physics goals of LBNE. Phase-I of LBNE[5] will use 708 kW of 120-GeV protons from Fermilab's Main Injector (MI) to produce a muon-neutrino or antineutrino beam aimed at a 10-kT ~~LAr detector~~ at a distance of 1300 km. The spectrum of neutrino energies detected at the far site in Phase-I is aligned with the first oscillation maximum, peaking in the E_ν = (2-4) GeV range.

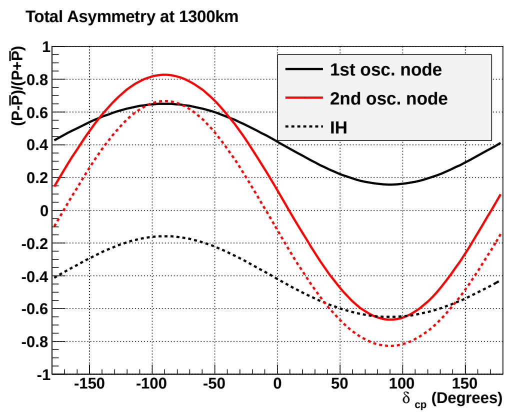

Figure 1: Total neutrino-antineutrino asymmetry for $\nu_\mu \rightarrow \nu_e$ appearance at 1300 km, at the first and second oscillation maxima, for normal and inverted hierarchy.

Figure 1 shows the total neutrino-antineutrino asymmetry for $\nu_\mu \rightarrow \nu_e$ appearance as a function of δ_{CP} at the first and second oscillation nodes for normal and inverted hierarchy. It is clear from Fig. 1 ~~that while there is some sensitivity to the CP phase at the first oscillation maximum, the effect of the CP phase is more dramatic at the second oscillation maximum, where E_ν = (0.2-1.5) GeV. In addition, for long-baselines, the degeneracy with mass hierarchy is broken at the second oscillation maximum.~~ Project X[6] will make it possible to produce high-intensity, low-energy neutrino beams that can probe this low-energy region. In this paper, we summarize [7], which argues that simultaneous, high-power operation of 8- and 60-GeV beams with a 200-kT water Cerenkov detector at a long baseline would provide sensitivity to $\nu_\mu \rightarrow \nu_e$ oscillations at the second oscillation maximum, allowing precise measurements of neutrino oscillation parameters independent of the mass hierarchy.

The kinematics of neutrino beam production dictates that the only way to produce significant yield of neutrinos at low energies is with high proton-beam power at low energies. With Project X, beam power from the MI can be maintained at or above 2 MW for proton energies of (60-120) GeV. Upgrading to an 8-GeV pulsed LINAC would provide up to 4 MW of 8-GeV beam power, only 270 kW of which is required by the MI to produce the 2-MW, 60-GeV beam. In this scenario, the Fermilab accelerator complex could simultaneously produce 2 MW of 60-GeV protons and 3 MW of 8-GeV protons. The resulting neutrino beams would have significant flux with $E_\nu < 1.5$ GeV, which would allow measurement of $\nu_\mu \rightarrow \nu_e$ oscillation at the second oscillation maximum at 1300 km.

Here, we consider a 200-kT water Cerenkov detector with reconstruction performance similar to Super-Kamiokande[8]. The efficiency of this detector for quasielastic neutrino scattering, which dominates at low neutrino energy, is ∼80%. The low-energy background level is significantly reduced relative to higher energy beams. With five years of running in simultaneous 8- and 60-GeV mode, it would be possible to measure $\sin^2(2\theta_{13})$ to within a few percent and δ_{CP} with an uncertainty of $\pm(5-10)^\circ$. The precision on $\sin^2(2\theta_{13})$ from $\nu_\mu \rightarrow \nu_e$ appearance, coming primarily from the 60-GeV beam, would be competitive with the precision expected from $\bar{\nu}_e$ disappearance in reactor neutrino experiments, and the two measurements would be complementary. The 8-GeV data is highly sensitive to δ_{CP} but the result is correlated with $\sin^2(2\theta_{13})$; in combination with the 60-GeV data, the 8-GeV data would provide a precise measurement of δ_{CP} with no need to rely on external constraints. A combined fit of the 8- and 60-GeV data is also expected to resolve the θ_{23} octant degeneracy. Finally, the 8-GeV, 60-GeV, and 120-GeV data would place independent constraints on neutrino oscillation parameters; new physics could be detected as inconsistent measurements of neutrino oscillation parameters in these three data sets.

In summary, the cleanest, most dramatic sensitivity to the CP phase comes from measurement of $\nu_\mu \rightarrow \nu_e$ oscillation at the second oscillation maximum, at long baseline, with a high-mass far detector. Project X, with an 8-GeV pulsed LINAC, could produce simultaneous low-energy, high-intensity beams which would probe this low-energy region, making precision measurements of neutrino oscillation parameters possible.

References

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